Heterogeneous distribution of ^{26}Al in the solar protoplanetary disk – insights from chondritic components and angrite meteorites.

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With a half-life of 0.73 Myr, the ^{26}Al-to-^{26}Mg decay system is the most widely used short-lived chronometer for understanding the formation and earliest evolution of the solar protoplanetary disk. However, the validity of ^{26}Al-^{26}Mg ages of meteorites and their components relies on the critical assumption that the canonical $^{26}Al/^{27}Al$ ratio of ~5×10^{-5} recorded by the oldest dated solids, calcium-aluminium-rich inclusions (CAIs), represents the initial abundance of ^{26}Al for the solar system as a whole.

Improved techniques for the measurements of magnesium isotopes by multiple collection inductively coupled mass spectrometry (MC-ICPMS) now allow for the determination of the radiogenic ^{26}Mg resulting from the in situ decay of ^{26}Al (μ^{26}Mg*) with an external reproducibility of ~2.5 ppm [1]. This permits, for the first time, to test the assumption of ^{26}Al homogeneity in the solar protoplanetary disk and, thus, the chronological significance of the ^{26}Al-^{26}Mg clock. Using these techniques, Larsen *et al.* [2] recently demonstrated that a high-precision bulk ^{26}Al-^{26}Mg isochron for CAIs and amoeboid olivine aggregates (AOA) from the pristine Efremovka carbonaceous chondrite defines an $^{26}Al/^{27}Al$ of (5.252 ± 0.019) × 10^{-5} and initial μ^{26}Mg value of −15.9 ± 1.4 ppm (Fig. 1). The μ^{26}Mg* value of the Efremovka CAI-AOA isochron at a solar $^{27}Al/^{24}Mg$ ratio of 0.101 is 22.2 ± 1.4 ppm, which is much higher than that defined by CI chondrites (μ^{26}Mg = 4.5 ± 1.0) as well as other bulk solar system materials with solar or near solar $^{27}Al/^{24}Mg$ ratios. Collectively, these data have been interpreted as reflecting widespread ^{26}Al heterogeneity in the protoplanetary disk at the time of CAIs formation. However, the observed μ^{26}Mg* heterogeneity could also predominantly reflect magnesium-isotope heterogeneity, although it is unclear how a late addition of ^{26}Al to the nascent solar system would result in a homogenous distribution of ^{26}Al, but a heterogeneous distribution of magnesium-isotopes.

Distinguishing between these two interpretations can be achieved by comparing U-Pb and ^{26}Al-^{26}Mg ages of pristine samples, given that the U-Pb chronometer provides absolute ages that are free from assumptions of parent nuclide homogeneity. We have thus initiated a study aimed at comparing U-Pb and ^{26}Al-^{26}Mg for samples with simple thermal histories such as CAIs, chondrules and angrites.

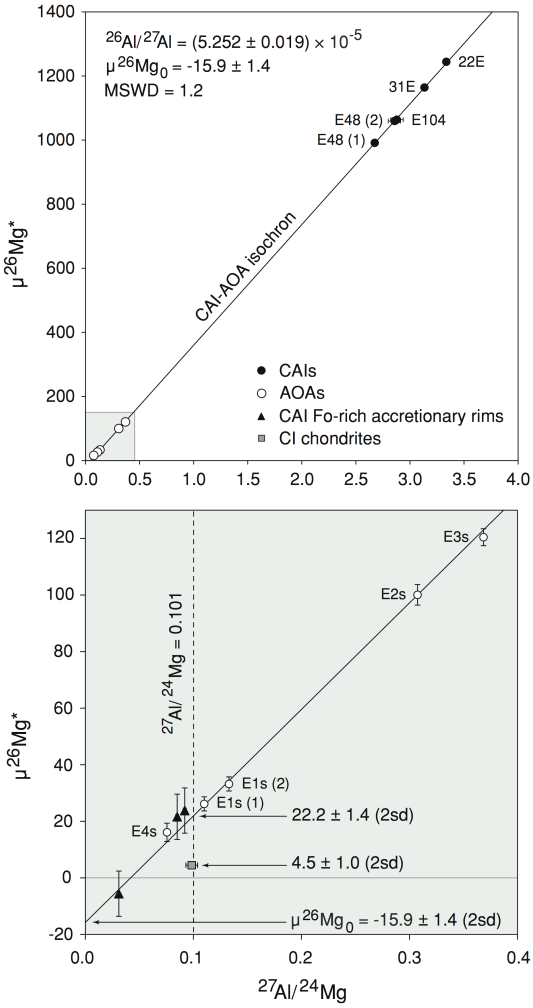

Figure 1: ^{26}Al-^{26}Mg evolution diagrams [2].

Angrite meteorites are the most alkali-depleted rocks in our solar system and they can be divided into plutonic and volcanic angrites [3]. Volcanic angrites record ancient crystallization Pb-Pb ages that are within ~4 Myr of CAI formation [4-5] and, thus, formed during the lifespan of ^{26}Al. Of particular interest is the NWA 1670 quenched angrite, as it contains significant amounts of olivine xenocrysts of up to 5 mm in size thereby allowing us to precisely define the initial ^{26}Mg* composition at the time of crystallization. Our new U-corrected Pb-Pb date for NWA 1670 indicates crystallization at 4564.37±0.19 Myr, making it the oldest known angrite. Individual olivine xenocrysts and multiple analyses of groundmass material of NWA 1670 define an

^{26}Al-^{26}Mg isochron yielding a slope corresponding to an ^{26}Al/^{27}Al of (6.14±0.88) × 10^{-7} and initial ^{26}Mg of −10.8±1.2 ppm. This corresponds to an age difference of 4.69±0.16 Myr between formation of CAIs and crystallization of NWA 1670, which is not consistent with the age difference of 2.93±0.25 Myr inferred from U-corrected Pb-Pb dating. This age discrepancy is similar to that observed between the ^{26}Al-^{26}Mg and Pb-Pb dates of the younger SAH 99555 and D'Orbigny quenched angrites, which record ^{26}Al-^{26}Mg ages that are systematically ~1.5 Myr younger than the Pb-Pb dates [6]. Reconciling the ^{26}Al-^{26}Mg ages of these angrites with their Pb-Pb dates require an initial ^{26}Al/^{27}Al of ~1.25 × 10^{-5} in the accretion region of the angrite parent body. This result supports the claim of ^{26}Al heterogeneity in the early solar system [2] and a reduced abundance of ^{26}Al in the accretion regions of asteroids and terrestrial planets compared to the ^{26}Al/^{27}Al value of ~5 × 10^{-5} defined by canonical CAIs.

To evaluate the extent of ^{26}Al heterogeneity in the inner solar system, we have extended our study to chondrules, as these represent the major constituent of chondrite meteorites and, by extension, the precursor material of asteroidal bodies and terrestrial planets. We obtained ^{26}Al-^{26}Mg ages through the internal isochron approach for three U-corrected Pb-Pb dated chondrules from the carbonaceous chondrite Allende and the unequilibrated ordinary chondrite NWA 5697 [7]. Internal isochron relationships were defined by combining *in situ* ^{26}Al-^{26}Mg systematics of Al-poor and Al-rich phases obtained by secondary ionization mass spectrometry (SIMS) at the of Hokkaido University with high-precision bulk analyses of the same chondrules by MC-ICPMS obtained at the University of Copenhagen. In detail, we investigated the internal ^{26}Al-^{26}Mg systematics of two ferro-magnesian porphytitic olivine-pyroxene chondrules from Allende (C30) and NWA 5697 (C1) as well as one barred olivine-pyroxene chondrule from NWA 5697 (C3). The C30, C1 and C3 chondrules have U-corrected Pb-Pb dates of 4567.32 ± 0.42 Myr, 4566.67 ± 0.43 Myr and 4566.02 ± 0.26 Myr, respectively [7]. Note that these chondrules record primitive initial Pb isotope compositions, which precludes a complex thermal history of their precursors.

Chondrule C30 defines an ^{26}Al-^{26}Mg isochron based on multiple analyses of spinel and olivine crystals as well as one bulk measurement that record an initial ^{26}Al/^{27}Al of (1.46 ± 0.29) × 10^{-5}. Chondrules C1 and C3 define ^{26}Al-^{26}Mg isochrons based on multiple analyses of olivines, glassy mesostasis and bulk measurements that record initial ^{26}Al/^{27}Al values of (8.15 ± 1.00) × 10^{-6} and (8.14 ± 2.8) × 10^{-6}, respectively. Thus, similar to angrite meteorites, the ^{26}Al-^{26}Mg systematics of the three chondrules analyzed here record ^{26}Al-^{26}Mg ages that are younger than their Pb-Pb dates by ~1.3-1.9 Myr.

The observed discrepancy between the ^{26}Al-^{26}Mg and Pb-Pb dates for the Allende and NWA 5697 chondrules could, in principle, reflect selective disturbance of the ^{26}Al-^{26}Mg system. However, the bulk of the U in chondrules is believed to be hosted by pyroxene which, similarly to the glassy mesostasis, is susceptible to thermal metamorphism. As such, disturbance of the ^{26}Al-^{26}Mg systematics is predicted to also be accompanied by U-Pb disturbance, which would be reflected by the loss of linearity in Pb-Pb isochron diagrams. The excellent linearity of the Pb-Pb isochron diagrams for the C30, C1 and C3 chondrules, coupled with the primitive Pb isotope compositions recorded by these three chondrules [7] is not consistent with disturbance of their U-Pb systematics. Therefore, we conclude that the ^{26}Al/^{27}Al ratios recorded by the chondrules reflect the initial abundance of ^{26}Al in their precursors at the time of crystallization inferred from the Pb-Pb dates.

The reduced ^{26}Al abundance in chondrule forming regions deduced from our measurements provides unequivocal evidence for heterogeneous distribution of ^{26}Al the time of CAI formation. We note that the initial abundance of ^{26}Al inferred for the various bulk solar system reservoirs correlates with their ^{54}Cr [2] as well as their ^{84}Sr [8], ^{43}Ca, ^{46}Ca and ^{48}Ca compositions [9], thus providing evidence for a relationship between the distribution of short-lived nuclides and that of stable isotope anomalies in the early solar system. Thus, similarly to the ^{54}Cr heterogeneity, we suggests that ^{26}Al heterogeneity in solar system objects reflects variable degrees of thermal processing of their precursor material, probably associated with volatile-element depletions in the inner solar system. In this view, CAIs and AOAs represent samples of the complementary gaseous reservoir enriched in ^{26}Al by thermal processing, which resulted in the widespread ^{26}Al depletions observed among inner solar system bodies.

A reduced abundance of ^{26}Al in the accretion regions of asteroidal bodies requires shorter timescales for the timing of accretion of differentiated planetesimals if melting resulted from ^{26}Al decay. Indeed, thermal modeling indicate that accretion within 100,000 years of CAI formation is necessary to fully melt a body that formed with an initial ^{26}Al/^{27}Al value of ~1 × 10^{-5}.

References:

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